APPLICATION NOTE

Low Resistance Option for 8400 Series HMS Part 1: Hall Measurements of Metals and Measurement of Resistance

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Introduction

The 84033 option for the Lake Shore Cryotronics 8400 Series extends the DC field Hall measurement capabilities of the system for the measurement of various low resistance materials. In this application note, we will specifically investigate the measurement of the Hall voltage in metals. In addition, we will compare the low resistance mode to the standard resistance mode and high resistance mode over a range of resistance values. Additional application notes will focus on the measurement of other materials.

The method

The low resistance option uses the Keithley Model 6220 DC current source and the Keithley Model 2182A nanovoltmeter in the delta mode. In this mode, the two Keithley instruments communicate over a dedicated interface to produce a square wave current source from the 6220 and synchronously detected voltage by the 2182A.

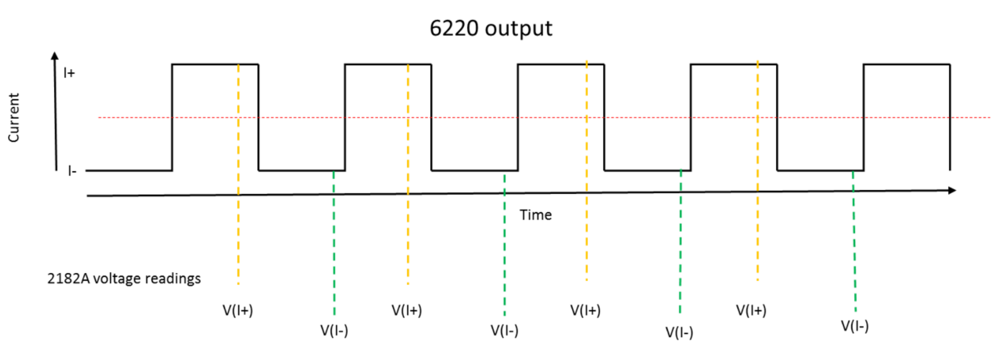

Figure 1—Schematic of Keithley delta mode as used with the 84033 low resistance option.

Figure 1 is a schematic of the measurement protocol. For each cycle of the 6220 output, the current reversed voltage is calculated as (V(I+)-V(I-))/2. Here, V(I+) is the 2182A reading for positive current and V(I-) is the 2182A reading for negative current. This is the same calculation as the current reversed voltage in the 8400 Series HMS standard and high resistance modes, except the measurements are made more quickly. In the delta mode, as configured in the 8400 system, the frequency of the square wave is approximately 24 Hz. In the standard and high resistance modes, the default time between current reversals is 10 s. The higher frequency of the delta mode reduces the 1/f noise in the measurement and results in a low noise for the measurement.

Hall measurement of metals

The sample and measurement conditions

The sample is an approximately 100 nm thick thin film of molybdenum. The carrier type in molybdenum is p type and the Hall coefficient is approximately 1.8×10^{-12} C/m^3. The Hall voltage vs. field was measured using a Model 8407 HMS. The field varied from -2 T to 2 T in 0.1 T steps. The sample was measured in the standard resistance mode with currents of 1 mA and 10 mA. The sample was also measured in low resistance mode with currents of 0.1 mA, 1 mA, and 10 mA. The Hall voltage was measured using DC field mode. In the 8400 Series system, it is not possible to use both AC field and low resistance mode simultaneously.

Results

Figure 2 is a plot of Hall voltage vs. field for both low resistance mode and standard resistance mode for a current of 1 mA.

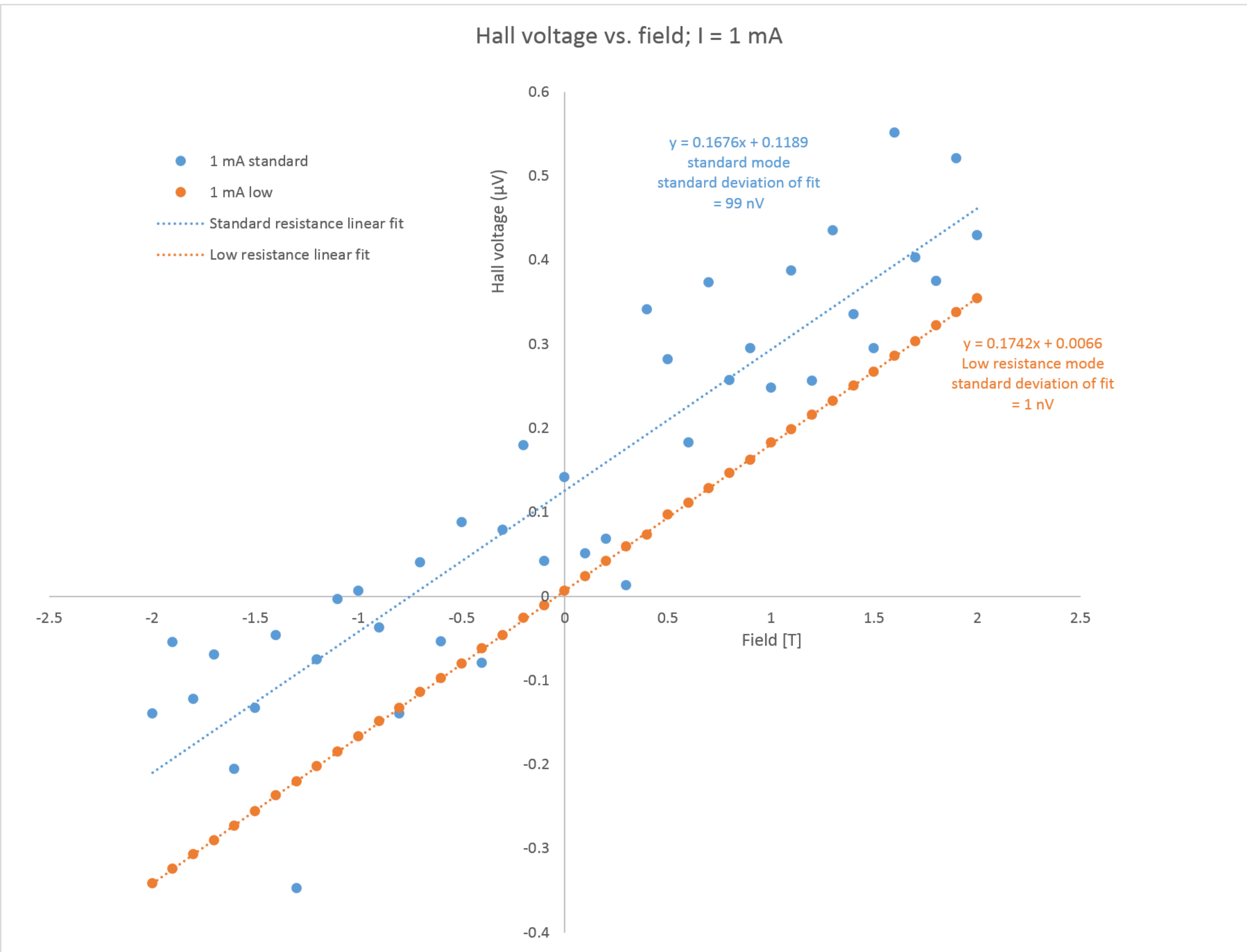

Figure 2—Hall voltage vs. field for both low and standard resistance modes with excitation current of 1 mA. The standard resistance data is in blue, and the low resistance data is in orange.

If the Hall voltage is in microvolts, the slope of the best fit line is $(10^6 \; I \; R_H)/t$, where R_H is the Hall coefficient, t is the thickness and I is the excitation current. In this case, the slope of the low resistance mode and the standard mode differ by only 2%. The Hall coefficient calculated from the slope is approximately 1.7×10^{-11} C/m^3. The standard deviation of the fit is 100 nV for the standard resistance mode and 3 nV for the low resistance mode. The noise of the standard resistance mode is 33 times larger than the low resistance mode.

	Current (mA)	Hall coefficient (C/m^3)	Standard error of Hall coefficient (C/m^3)	Hall coefficient % error	Standard deviation of fit (nV)
Low resistance mode	10	1.74E-11	4.56E-14	0.3%	3
Standard resistance mode	10	1.74E-11	1.37E-12	8.0%	100
Low resistance mode	1	1.74E-11	1.46E-14	0.1%	1
Standard resistance mode	1	1.68E-11	1.34E-12	8.0%	99
Low resistance mode	0.1	1.72E-11	4.22E-14	0.2%	3

Table 1—Summary of all measurements. The standard deviation of the fit does not depend on the excitation current.

Discussion

The standard deviation of the fit does not depend on the excitation current over the current range investigated here. The standard deviation of fit for the standard resistance mode is 100 nV, and the standard deviation of the fit for the low resistance mode is 3 nV. These noise values are consistent with the noise of the 2182A voltmeter. In this resistance range, the voltmeter noise dominates the measurement noise. From this, we can calculate the standard deviation of the resistance as the standard deviation of the voltage readings divided by the current. The largest current the 8400 system can use is 100 mA. Table 2 is a summary of the resistance noise assuming a current of 100 mA and a current of 1 mA. For this table, the minimum detectable resistance is defined as 10 times the noise.

	Resistance noise at 100 mA (µΩ)	Resistance noise at 1 mA (µΩ)	Minimum detectable resistance at 100 mA (µΩ)	Minimum detectable resistance at 1 mA (µΩ)
Low resistance mode	0.03	3	0.3	30
High resistance mode	1	100	10	1000

Table 2—Summary of resistance noise assuming excitation current of 100 mA and 1 mA. Minimum detectable resistance is defined as 10 times the resistance noise.

Measurement of resistance

The sample and measurement conditions

For this measurement, standard 1% resistors with value 11.3 Ω, 511 Ω, 100 kΩ, and 1 MΩ were measured with different currents. All resistors were measured in low resistance mode. In addition, the 11.3 Ω, 500 Ω, and 100 kΩ resistors were measured in standard resistance mode and the 100 kΩ and 1 MΩ resistors were measured in high resistance mode.

The low resistance mode provides a lower noise measurement compared to the standard high resistance modes. For resistance above 100 kΩ, the accuracy of the low resistance mode degrades. Notice the 1 MΩ resistor is measured as 934 kΩ, about a 6% error. This error is due to the capacitance of the cables causing a phase shift of the voltage measurement that is not compensated.

Nominal resistance	Current	Low resistance	Standard deviation	Standard resistance	Standard deviation	High resistance	Standard deviation
11.3 Ω	1 mA	11.3 Ω	2.19E-05 Ω	11.3 Ω	2.08E-04 Ω	—	—
11.3 Ω	100 mA	11.3 Ω	2.48E-06 Ω	11.3 Ω	1.43E-05 Ω	—	—
511 Ω	1 mA	511 Ω	1.16E-04 Ω	511.0 Ω	6.88E-01 Ω	—	—
100 kΩ	100 nA	99.5 kΩ	1.23 Ω	99.8 kΩ	145 Ω	99.5 kΩ	8.52 Ω
100 kΩ	1 µA	99.4 kΩ	0.095 Ω	99.6 kΩ	7.71 Ω	99.5 kΩ	1.73 Ω
1 MΩ	10 nA	0.934 MΩ	371 Ω	—	—	0.997 MΩ	67 Ω
1 MΩ	100 nA	0.935 MΩ	404 Ω	0.999 MΩ	1780 Ω	0.996 MΩ	9.53 Ω
1 MΩ	1 µA	0.934 MΩ	287 Ω	0.998 MΩ	130 Ω	0.997 MΩ	13.9 Ω

Table 3—Summary of results of resistance measurements using low, standard, and high resistance modes.

Conclusion

The standard resistance mode of the 8400 Series HMS system has a noise floor of 100 nV. This is determined from a linear fit of the Hall voltage vs field. Using the low resistance option will decrease this voltage noise to 3 nV. Assuming a measurement current of 100 mA, this implies a noise floor for a resistance as 1 μΩ for the standard resistance mode and 0.03 μΩ for the low resistance mode.

For resistance measurement, the low resistance measurement provided lower noise for resistances up to 100 kΩ.

The low resistance option for the 8400 Series system provides better signal to noise ratio, compared to the standard resistance mode, for resistance measurements up to 100 kΩ and Hall voltages measured with DC fields on samples with less than 100 kΩ resistance.

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